

Attachment "1"

Evidence for Detection of a Moving Magnetic Monopole

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A very heavy particle passed through a balloon-borne stack of Cherenkov film, emulsion, and Lexan sheets. In 33 Lexan sheets it produced tracks expected of either a nucleus with $125 \leq Z \leq 137$ and $\beta \leq 0.92$ or a magnetic monopole with $g = 137e$. Its track structure in emulsion indicated it was moving downward with $\beta = 0.5^{+0.1}_{-0.05}$ and was either a nucleus with $Z \approx 80$ or a monopole with $g = 137e$. These facts strongly favor identification of the particle as a magnetic monopole of strength $g = 137e$ and mass $> 200m_p$.

In the last of our series of balloon flights to study ultraheavy cosmic rays ($Z \geq 60$) at low geomagnetic cutoff, the multilayer stack, 20 m² in area, shown in Fig. 1, was exposed for 2.6 days at an atmospheric depth of ~ 3 g/cm² near Sioux City, Iowa, on 18 September 1973. Here we present our analysis of one event that differs from any seen in previous balloon flights¹ or in the Skylab ultraheavy-cosmic-ray experiment.²

The event was found in a stereomicroscopic scan of the emulsion layer and was recorded as having $Z \approx 80$ and $\beta = 0.5^{+0.1}_{-0.05}$ on the basis of track-structure measurement made with an eyepiece reticle and a microscope. The estimates of Z and β guide us in choosing the optimum times for chemically etching the portions of the Lexan sheets along a particular event. Cone-length measurements in the Lexan then yield much more precise estimates of charge and velocity. The fast-film Cherenkov detectors furnish independent velocity estimates for $Z \geq 70$ and $\beta > 0.68$. Figure 1 summarizes the information derived from each type of detector. Only the interpretation of the particle as a magnetic monopole with $g = 137e$ and $\beta \approx 0.5$ is consistent with all the available information.

Figure 2 shows the data from the Lexan detector. The triangles represent data from a 20-h etch and the solid circles for a 30-h etch in a separate tank.³ All measurements were made by two observers. The points reproduce to within $\pm 0.05 \mu\text{m/h}$.

In previous analyses^{2,3} of ultraheavy cosmic rays we have found the etch rate v_T depends on ionization rate approximately as

$$v_T = \text{const}(Z^*/\beta)^4, \quad (1)$$

where Z^* is the effective charge. The scale at the bottom of Fig. 2 is the estimated charge assignment if $\beta \approx 1$. The best fit to the data is given by a zero slope (rate of change of etch rate with depth), corresponding to a hypothetical charged particle with $Z \approx 137$ and $\beta \approx 1$. For the maximum slope, S_{max} , consistent with the data (84% confidence), the charge is $Z \approx 125$ and $\beta \approx 0.92$. In no previous flight with Lexan detectors has an event been found with $Z \geq 96$. This is reasonable because ²⁴⁷Cm is the heaviest known nuclide with a half-life (in its rest frame) greater than 10⁶ yr.

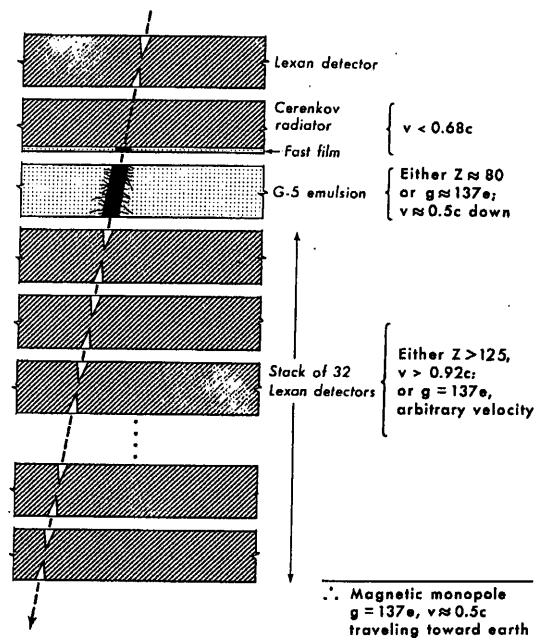


FIG. 1. Stack of balloon-borne detectors.

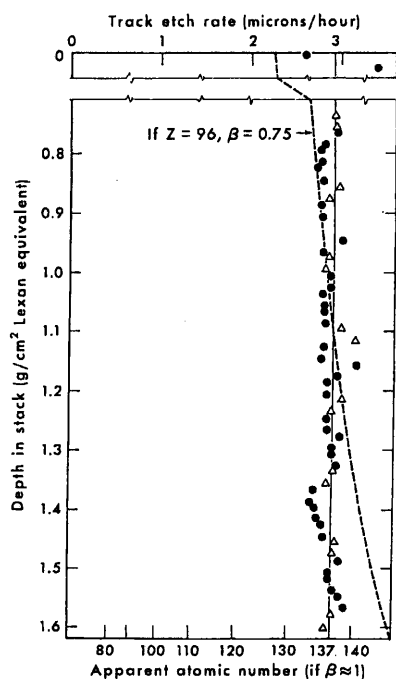


FIG. 2. Etch-rate data. See text. Emulsion data rule out dashed curve or any fit to a nucleus with $\beta > 0.5^{+0.1}_{-0.05}$.

The dashed curve in Fig. 2 shows the best fit to the data for a nucleus of $Z = 96$; its velocity must be $\sim 0.75c$; its slope is ~ 18 times S_{max} . The ionization rate of a magnetic monopole of strength g is given⁵⁻⁷ by replacing Z^*e by $g\beta$, so that for a monopole Eq. (1) must be replaced by

$$v_T = \text{const}(g/e)^4. \quad (2)$$

The solid line in Fig. 2 is consistent with a monopole of strength twice the minimum strength $g_0 = \hbar c/2e = (137/2)e$ of Dirac's hypothetical magnetic monopole.⁴ Thus, the etch-rate data admit of only two alternatives:

- (1) The particle was a nucleus with $Z \lesssim 125$, $\beta \gtrsim 0.92$.
- (2) The particle was a monopole with $g = 137e$ and any velocity sufficient to penetrate the 1.6-g/cm² stack.

The data from the nuclear emulsion and Cherenkov film enable us to reject the first alternative. One of us⁸ has extended the track model of Kobetich and Katz⁹ and their electron-energy-deposition algorithm¹⁰ to obtain detailed predictions of ion-track structure from the track core out to the maximum lateral extent of the δ rays for wide ranges of Z and β . Subsequently, we¹¹ modified

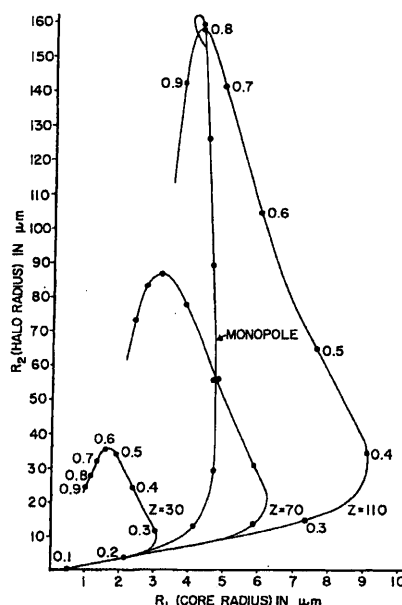


FIG. 3. Method of estimating charge and velocity from track structure in emulsion. See text. Numbers along curves give $\beta = v/c$.

these calculations to include the Mott cross section¹² rather than the Rutherford cross section. These results are in agreement with our accumulated experience from almost 100 ultraheavy-cosmic-ray events, and allow us to predict monopole-track structure by the substitution $Z^* = 137\beta$. Katz and Butts⁷ predicted monopole-track core widths based on the Rutherford cross section, but did not consider structure outside of the core region. A useful way to display our results is to plot R_1 , the radius at which the probability of grain development is 0.4 versus R_2 , the radius at which the probability of grain development is 0.001. R_1 corresponds to the core radius and R_2 to the limit of visual perception of a signal above background. Figure 3 contains results for $Z = 30$, 70, and 110, and for a monopole with $g = 137e$.

Because of the steepness of the track, R_1 could not be measured accurately but was $\sim 6 \mu\text{m}$. The observed R_2 was $55 \mu\text{m}$, consistent with a monopole with $\beta \approx 0.5$, but totally inconsistent with the R_2 ($130 \mu\text{m}$) expected for a nucleus with $Z > 125$ and $\beta > 0.92$. Observations of Fe tracks that stopped in the Lexan showed that the emulsion had normal sensitivity.

Our measurements show that, among the identifiable individual δ rays, downward-directed tracks outnumber upward-directed tracks by at

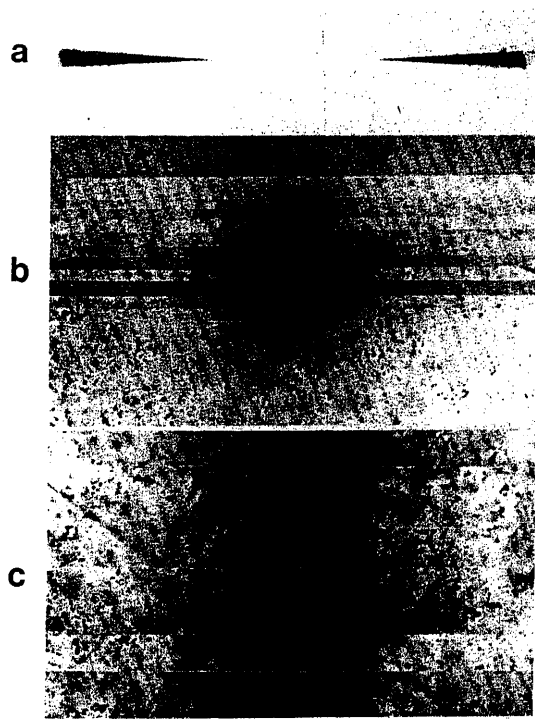


FIG. 4. Photomicrographs of the monopole track in (a) a Lexan sheet (epoxied, sliced, and viewed edge-on), and (b) G-5 emulsion (viewed nearly vertically). In (c), note the greater lateral extent of δ rays from a nucleus with $Z \approx 92$ and $\beta \approx 0.6$.

least 5 to 1. We conclude that the monopole was moving downward.

Figure 4 shows photomicrographs of the monopole track in one sheet of Lexan and in the emulsion, together with a photomicrograph of the track of the heaviest nucleus found in the flight. From its R_1 ($\sim 5 \mu\text{m}$) and R_2 ($110 \mu\text{m}$) in emulsion it was estimated to have $Z \approx 95$, $\beta \approx 0.65$. It came to rest in the Lexan stack. Measurements of its etch pits showed that $Z \approx 92$ and $\beta \approx 0.6$ at the emulsion.

A fast-film Cherenkov detector consisting of a thin plastic Cherenkov radiator, coated with Eastman Kodak 2485 film, records an elliptical image at the trajectory of a charged particle of $Z \geq 70$ and $\beta > \beta_{\text{crit}} \approx n^{-1}$, where n is the refractive index of the radiator.^{3,13} The intensity of the image is proportional to $(Ze)^2(1 - n^{-2}\beta^{-2})$ for a charged particle and to $g^2(n^2 - \beta^{-2})$ for a monopole. We have examined the appropriate region of our fast-film Cherenkov detector and have found a small ion-

ization spot but no elliptical Cherenkov image. Eight other regions traversed by high-energy, high- Z nuclei during this flight showed normal Cherenkov images. We conclude that the particle in question had a velocity $\beta \leq 0.68$ in the Cherenkov radiator.

Independent of all details of calibration of response of the Lexan and the emulsion, the essence of our observations is that we have found a particle of velocity $\sim 0.5c$ that ionized heavily and at a constant rate as it slowed down through 1.6 g/cm^2 of matter. This constancy of ionization rate was first shown by Dirac⁴ to be a property of magnetic monopoles. A particle with only electric charge and velocity $0.5c$ would have to have an enormous ratio of mass to charge to fit the data ($> 10^4$ proton masses and $Z \approx 70$). Neither a Lee-Wick abnormal nucleus¹⁴ nor a small, charged black hole¹⁵ is consistent with the evidence.

We conclude that we have detected a magnetic monopole of strength $g = 137e$ and velocity $(0.5^{+0.1}_{-0.05})c$. In order to penetrate the $\sim 1\text{-g/cm}^2$ Lexan stack its energy must exceed 32 GeV , which means that its mass must exceed ~ 200 proton masses. Its existence rules out the existence of free quarks or other fractionally charged particles.

Based on this one event out of numerous balloon flights and one satellite exposure of large detectors of heavily ionizing particles, the flux of monopoles of strength $137e$ near the top of the atmosphere with velocity sufficient to penetrate track detectors is $\sim 10^{-13} \text{ cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}$. The apparent conflict between this flux and the negative results obtained in previous monopole searches¹⁶ places strong constraints on the properties of monopoles.

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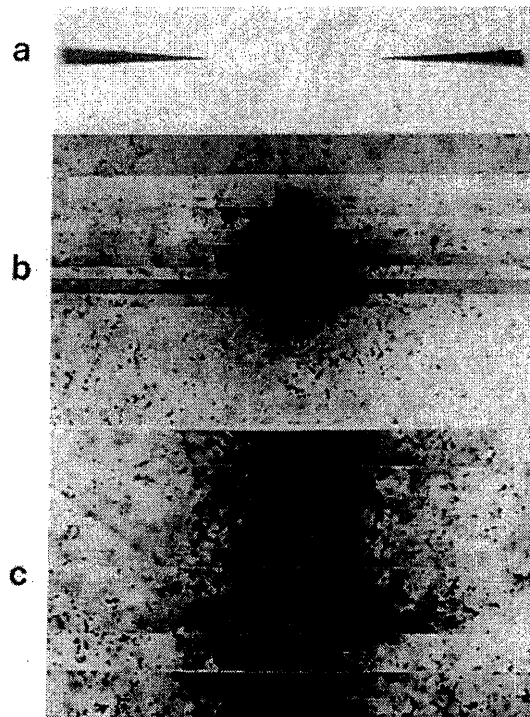


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